HCN versus HCO^+ as dense molecular gas mass tracer in Luminous Infrared Galaxies

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ABSTRACT

It has been recently argued that the HCN J=1–0 line emission may not be an unbiased tracer of dense molecular gas ($n \gtrsim 10^4\,\mathrm{cm}^{-3}$) in Luminous Infrared Galaxies (LIRGs: $L_{FIR} > 10^{11}\,L_\odot$) and HCO^+ J=1–0 may constitute a better tracer instead (Graciá-Carpio et al. 2006), casting doubt into earlier claims supporting the former as a good tracer of such gas (Gao & Solomon 2004; Wu et al. 2006). In this paper new sensitive HCN J=4–3 observations of four such galaxies are presented, revealing a surprisingly wide excitation range for their dense gas phase that may render the J=1–0 transition from either species a poor proxy of its mass. Moreover the well-known sensitivity of the HCO^+ abundance on the ionization degree of the molecular gas (an important issue omitted from the ongoing discussion about the relative merits of HCN and HCO^+ as dense gas tracers) may severely reduce the HCO^+ abundance in the star-forming and highly turbulent molecular gas found in LIRGs, while HCN remains abundant. This may result to the decreasing HCO^+/HCN J=1–0 line ratio with increasing IR luminosity found in LIRGs, and casts doubts on the HCO^+ rather than the HCN as a good dense molecular gas tracer. Multi-transition observations of both molecules are needed to identify the best such tracer, its relation to ongoing star formation, and constrain what may be a considerable range of dense gas properties in such galaxies.

Subject headings: galaxies: starbursts – galaxies: active – ISM: molecules – ISM: HCN, HCO^+ – radio lines: galaxies

1. Introduction

The HCN and HCO^+ molecules are the most abundant H_2 mass tracers after CO, whose much higher dipole moments ($\mu_{10} \sim 2.98, 3.92$ Debye for HCN, HCO^+ J=1–0 versus

$\mu_{10} = 0.11$ Debye for CO J=1–0) makes their transitions excellent tracers of dense molecular gas in galaxies. This is due to critical densities of rotational transitions being $n_{crit} \propto \mu^2 \nu^3_{J+1\,J}$ (for optically thin lines at frequency $\nu_{J+1\,J}$), allowing the HCO^+ and HCN lines to trace $\sim 100 - 500$ times denser gas than corresponding (in rotational level) CO transitions. Early pioneering studies of the dense molecular gas in galaxies using HCN and HCO^+ transitions (Nguyen-Q-Rieu et al. 1992; Solomon, Downes, & Radford 1992; Paglione et al. 1997), have been recently followed by surveys of large galaxy samples in HCN J=1–0 (Gao & Solomon 2004a, 2004b), made possible by major advancements in receiver sensitivity in large mm/sub-mm telescopes. Rotational transitions of CS are also important dense gas mass tracers (e.g. Plume et al. 1997; Shirley et al. 2003), but are $\sim 2 - 6$ times weaker than those of HCN (Helfer & Blitz 1993; Paglione et al. 1995). Thus, until the commissioning of the next generation of mm/sub-mm radio telescope arrays, the HCN and HCO^+ rotational lines are likely to remain the dense gas mass tracers of choice, especially in the extragalactic domain.

The most prominent and intriguing result from the recent HCN J=1–0 surveys is a nearly constant star formation efficiency *per dense molecular gas mass*, manifesting itself as a tight $L_{FIR} - L_{HCN}$ correlation and a nearly constant L_{FIR}/L_{HCN} versus L_{FIR} in Luminous Infared Galaxies (LIRGs). In those systems their IR luminosity ($> 10^{11}\,L_\odot$) is powered by starbursts that are particularly prominent in the Ultra Luminous Infrared Galaxies (ULIRGs) with $L_{IR} > 10^{12}\,L_\odot$ (e.g. Genzel et al. 1998), while the luminosity of the HCN J=1–0 line ($n_{crit} \sim 2 \times 10^5\,cm^{-3}$) is used as a proxy for the dense molecular gas mass. In a recent paper Wu et al. (2006) confirmed the $L_{FIR} - L_{HCN}$ linear correlation and extended it down 8 orders of magnitude to individual Giant Molecular Clouds (GMCs) found in the Galaxy, while locating also its breakdown at $L_{IR} < 10^{4.5}\,L_\odot$ where the corresponding GMC masses become so small that the top of the IMF (responsible for the bulk of the FIR luminosity per GMC) becomes undersampled. If true, such a universal star formation efficiency of the dense molecular gas allows a common frame for understanding star formation and its relation to the molecular gas across cosmic epoch, and ties this process to an obscuration-free indicator, the rotational lines of HCN. The stakes for identifying dense molecular gas mass tracers in galaxies and their relation to star formation have been recently raised by the detection of HCN transitions in starbursts at high redshifts (Solomon et al. 2003; Wagg et al. 2005), but also with recent work casting doubt on the reliability of HCN as such a tracer and suggesting the transitions of the molecular ion HCO^+ as an alternative (Graciá-Carpio et al. 2006).

In this work new HCN J=4–3 ($n_{crit} \sim 8.5 \times 10^6\,cm^{-3}$) observations of four prominent LIRGs are presented and used to demonstrate a surprisingly wide range of the physical conditions for the dense molecular gas fueling their starbursts. A simple corollary of this is that the J=1–0 transition of either HCN or HCO^+ may yield very unreliable estimates of the dense gas mass in such galaxies. Moreover, well-known effects particular to the molecular ion chemistry of HCO^+, are used to argue that its abundance can be greatly reduced in the ISM environments found in LIRGs. This can be partly or fully responsible for a decreasing HCO^+/HCN J=1–0 line ratio with IR luminosity observed recently in LIRGs by Graciá-Carpio et al., and calls for multi-transition observations of both molecules to discern the degree in which they trace the same dense gas phase, its excitation conditions, mass, and relation to the often spectacular starbursts found in such galaxies.

2. Motivation and observations

Early studies of the dense molecular gas in LIRGs using HCN J=1–0 observations were the first to suggest a potentially constant star formation efficiency per dense gas mass (Solomon et al. 1992). Recognizing the importance of the dense gas (defined as gas with $n(H_2) \geq 10^4\,\mathrm{cm}^{-3}$) as the direct "fuel" of their prodigious star formation an HCN and CO, ^{13}CO multi-transition line survey was initiated with the James Clerk Maxwel Telescope (JCMT) in Hawaii (US), and the IRAM 30-m telescope at Pico Veleta (Spain) for a sample of 30 LIRGs. Once completed and combined with data from the literature this survey will yield a database of CO J=1–0, 2–1, 3–2, 4–3, HCN J=1–0, 3–2, 4–3, and at least one ^{13}CO transition for all the galaxies in the sample. The hereby reported HCN J=4–3 and CO J=3–2 line measurements are for the (U)LIRGs: Arp 220, Arp 193, NGC 6240 and the ULIRG/QSO Mrk 231, galaxies whose large HCN J=1–0 line luminosities (larger than the CO J=1–0 luminosity of the Milky Way) were the first to be measured for this class of objects by Solomon et al. (1992).

The observations were conducted with the 15-m JCMT[1] during several periods starting from July 1999 up to January 2006, with the receiver B3 tunned SSB to the frequencies 354.734 GHz (HCN J=4–3) and 345.796 GHz (CO J=3–2). The Digital Autocorrelation Spectrometer (DAS) was the backend used, set at its widest ~ 1.8 GHz ($\sim 1520 - 1560\,\mathrm{km\,s^{-1}}$) bandwidth, except for the HCN J=4–3 measurements of Mrk 231 and Arp 193 where a dual-channel mode (two orthogonal polarizations) with $\sim 920\,\mathrm{MHz}$ ($\sim 777\,\mathrm{km\,s^{-1}}$) bandwidth was used for increased sensitivity. Rapid beam switching with frequencies of 1-2 Hz at a beam throw of $30'' - 60''$ (Az) produced exceptionally flat baselines, and pointing checks every hour left $\lesssim 3''$ (rms) of pointing residuals for the $\sim 14''$ (HPBW) beam. Observations of Mars and Uranus were used to obtain the aperture efficiency, found to be within the expected $\sim 10\%$

[1]The JCMT is operated by the Joint Astronomy Center on behalf of the United Kingdom Particle Physics and Astronomy Research Council (PPARC), the Netherlands Organisation for Scientific Research, and the National Research Council of Canada.

of the nominal value of $\eta_a = 0.53$. Finally frequent observations of spectral line standards such as OMC1, W75N and W3(OH) with high S/N were made in order to ensure the proper overall line calibration and estimate its uncertainty ($\sim 15\%$).

All the spectra are shown in Figure 1, and the HCN J=4–3 velocity-integrated line flux densities were estimated from

$$\int_{\Delta V} S_\nu dV = \frac{8k_B}{\eta_a \pi D^2} \int_{\Delta V} T^*_A dV = \frac{15.6(\mathrm{Jy/K})}{\eta_a} \int_{\Delta V} T^*_A dV, \tag{1}$$

(D=15 m, point sources assumed). These fluxes, along with those of the HCN J=1–0 line obtained from the literature, can be found in Table 1.

3. Dense gas in LIRGs: a surprising range of excitation

The deduced $r_{43} = (4-3)/(1-0)$ HCN ratios (Table 1) *imply a surprisingly wide range of physical conditions for the dense molecular gas phase,* with the sub-thermal value of $r_{43} = 0.27$ found for the ULIRG/QSO Mrk 231 with the largest HCN J=1–0 luminosity of the four, while $r_{43} \sim 1$ in Arp 220 implies a well-excited and dense gas phase. In Arp 193 its weak HCN J=4–3 line emission ($\gtrsim 100$ weaker than its CO J=3–2 line) remains undetected down to an impressively low limit, corresponding to $r_{43} \lesssim 0.12$. Large differences in the physical conditions of the dense molecular gas in galaxies with otherwise similar FIR and low-J CO line luminosities is well known for systems with $L_{FIR} \sim 10^{10}\, L_\odot$ (Jackson et al. 1995). The present work finds such excitation variations to be even larger in LIRGs with $\sim 10-100$ times larger star formation rates (and presumably larger still supplies of dense gas).

Such a large excitation range can be detrimental when either the HCN or HCO^+ J=1–0 line luminosity is used to obtain dense molecular gas mass using a standard proportionality factor as recently advocated by Gao & Solomon (2004a). To briefly illustrate this point a Large Velocity Gradient (LVG) code with HCN collisional rates adopted from LAMDA[2] is used to find the physical states compatible with the extreme values of $r_{43} \leq 0.12$ (Arp 193), and $r_{43} \sim 1$ (Arp 220). The search is further constrained by $T_k \geq T_{dust}$ expected for the thermally decoupled gas and dust reservoirs ($T_{kin} \to T_{dust}$ only in the densest $n \gtrsim 10^{4-5}\, cm^{-3}$, most FUV-shielded and quiescent regions inside GMCs), where T_{dust}(Arp 220) ~ 45 K and T_{dust}(Arp 193) ~ 30 K; (Lisenfeld, Isaak, & Hills 2000).

[2]Leiden Atomic and Molecular Database: http://www.strw.leidenuniv.nl/~moldata/ (Schöier et al. 2005)

For Arp 193 typically $n(H_2) \sim (1-3) \times 10^4\,cm^{-3}$ (e.g. for $T_k = 30-40\,K$ and $T_k = 60-65\,K$), but can also be as low as $\sim 3 \times 10^3\,cm^{-3}$ (for $T_k = 70-75\,K$) and even $\sim 10^2\,cm^{-3}$ (for $T_k \geq 80\,K$). Thus the HCN line emission in Arp 193 *is compatible with the complete absence of a dense and massive molecular gas phase*, and in such a case HCN J=1–0 would be tracing the same gas phase as the low-J CO transitions. This is manifestly not the case for $r_{43} \sim 1$, which typically implies $n(H_2) \sim (1-3) \times 10^5\,cm^{-3}$ (for $T_k = 40-95\,K$). It must be noted that in al LVG solutions HCN J=1–0 remains optically thick, a result easily demonstrated using simple LTE arguments where,

$$\frac{\tau_{10}(\mathrm{HCN})}{\tau_{10}(\mathrm{CO})} = \frac{\nu_{10}(\mathrm{HCN})}{\nu_{10}(\mathrm{CO})} \left[\frac{\mu_{10}(\mathrm{HCN})}{\mu_{10}(\mathrm{CO})}\right]^2 \left(\frac{1-e^{-h\nu_{10}(\mathrm{HCN})/k_B T_k}}{1-e^{-h\nu_{10}(\mathrm{CO})/k_B T_k}}\right) \left[\frac{\mathrm{HCN}}{\mathrm{CO}}\right], \tag{2}$$

($h\nu_{10}(CO)/k_B \sim 5.53\,K$, $h\nu_{10}(HCN)/k_B \sim 4.25\,K$). For a typical $[HCN/CO] \sim 2 \times 10^{-4}$ and $T_k \sim (15-60)\,K$, $\tau_{10}(HCN) \sim 0.1 \times \tau_{10}(CO) > 1$ (since $\tau_{10}(CO) \gg 1$ for the dense gas phase traced by HCN). Similar results are obtained for HCO^+(1–0), reflecting the fact that their large dipole moments offset their lower abundances relative to CO, and keep their J=1–0 transition optically thick for the dense molecular gas. Observations of HCN, $H^{13}CN$ and HCO^+, $H^{13}CO^+$ (Nguyen-Q-Rieu et al. 1992; Paglione et al. 1997) offer further support for a mostly optically thick HCN and HCO^+ J=1–0 line emission.

It must be noted that LVG modeling of line ratios of molecular line emission emerging from entire galaxies yields only a crude average of the prevailing physical conditions of the molecular gas, even if one were to assume the entire emission to be reducible to that of a typical Galactic GMC. Indeed, well-known density-size hierarchies found in such clouds, where $\langle n(R) \rangle \propto R^{-1}$ (R is the cloud or cloud sub-region size, e.g. Larson 1981), reduce the LVG solutions for densities as mere approximations of the mean density of the cloud regions where these are large enough to excite the transitions used.

The mass of the HCN/HCO^+-emitting dense gas can be estimated in a manner akin to that used for total molecular gas mass estimates from the ^{12}CO J=1–0 line luminosity since the same arguments about optically thick line emission emanating from an ensemble of self-gravitating, non-shadowing (in space or velocity), clouds remain applicable (e.g. Dickman, Snell, & Schloerb, 1986). Thus

$$M_{\mathrm{dense}}(H_2) \approx 2.1 \frac{\sqrt{\langle n(H_2) \rangle}}{T_{b,x}^{(10)}} \left(\frac{L}{\mathrm{K\,km\,s^{-1}\,pc^2}}\right) M_{\odot}, \tag{3}$$

where $T_b^{(10)}$ is the emergent line brightness temperature, and $L = \int\int T_b^{(10)} da dV$ for HCN or HCO^+ J=1–0 integrated over the entire velocity profile and area of the source (e.g. Radford, Solomon, & Downes 1991a). From the LVG solutions the coefficient in Equation 3 is found to be $X_{HCN} \sim 10 - 30$ for the high excitation gas in Arp 220, but $X_{HCN} \sim 15 - 100$ for Arp 193, which may lack a dense *and* massive gas phase altogether (i.e. there are LVG solutions with $n < 10^4\,cm^{-3}$). Thus $M_{dense}(H_2)$ estimates using only HCN or HCO^+ J=1–0 line luminosities can be uncertain by factors of ~ 10, and results based on them must be revisited when better constraints on the excitation of the dense gas become available. For example, much of the significant scatter around a constant star formation efficiency per dense gas mass (approximated by L_{FIR}/L_{HCN}) versus star formation rate ($\propto L_{FIR}$) found by Gao & Solomon (2004b), could be due to the potentially large range of the HCN excitation revealed here. *The case of Arp 193, a prominent LIRG ($L_{FIR} \sim 4 \times 10^{11}\,L_\odot$) with a large HCN J=1–0 line luminosity, in which a massive and dense gas phase may not even be present,* demonstrates how singularly wrong results can be obtained for the gas mass at $n \geq 10^4\,cm^{-3}$ in such systems if the simple approach of Equation 3 were to be used.

This stands in contrast to the X_{CO} factor used throughout the literature to obtain total H_2 gas mass in LIRGs from the ^{12}CO J=1–0 line luminosity (e.g. Tinney et al. 1990; Sanders et al. 1991). The latter line remains well excited under most typical conditions found in GMCs ($n_{cr} \sim 400/\tau_{10}\,cm^{-3} \sim (100 - 200)\,cm^{-3}$), a notion supported by CO line ratios that vary over a much smaller range of values (e.g. Braine & Combes 1992; Devereux et al. 1994; Dumke et al. 2001; Narayanan et al. 2005) and a X_{CO} found to be robust within factors of ~ 2 (e.g. Young & Scoville 1991). Its applicability is hindered only in metal poor, FUV-intense environments where CO but not H_2 dissociates (e.g. Maloney & Black 1988; Israel et al. 1993, Israel 1997), and for highly excited, non-virialized, gas found in ULIRGs. In the latter case an X_{CO} factor remains applicable, but with smaller values than those in the Galactic (and mostly virialized) GMCs (Solomon et al. 1997; Downes & Solomon 1998).

4. HCN versus HCO^+ as a dense gas mass tracer in LIRGs

Since the HCN and HCO^+ J=1–0 lines in the dense gas phase usually have $\tau_{10} > 1$, estimates of its mass do not explicitely depend on the specific abundances (cf. Equation 3). These are then of no great importance, and it could be argued that either molecule can trace the dense gas mass equally well. However, in a manner similar to the mostly FUV/metallicity-regulated extent of the optically thick CO J=1–0 emission relative to the total size of a molecular cloud (e.g. Pak et al. 1998; Bolatto, Jackson, & Ingalls 1999), the HCN and HCO^+ abundances partly determine the fraction of the dense gas that can be traced by their luminous and optically thick J=1–0 line emission within a given GMC (with the level of line excitation being the other determining factor).

In the dense cosmic-ray-dominated regions of GMCs where much of the HCN and HCO^+ line emission originates, the CR-induced formation of H_3^+ is the critical initiator of the networks that eventually yield these two molecules. The main reason for expecting $[HCN/HCO^+] \gtrsim 1$ for the dense gas in such regions stems from the fact that HCN, being neutral, can remain abundant while HCO^+ as a molecular ion is removed via recombination with free electrons. Hence, *while both HCN and HCO^+ are sensitive to the CR-produced abundance of H_3^+, HCO^+ is in addition very sensitive to the ambient free electron abundance x(e),* and even small increases of the latter can lead to its severe depletion. This important point has been neglected from the ongoing discussion regarding the relative merits of HCN and HCO^+ as effective dense gas mass tracers (e.g. Graciá-Carpio et al. 2006).

This HCO^+ abundance sensitivity to the ambient x(e) is well-known and used in studies of dense cloud cores throughout the literature to obtain the latter using the former (e.g. Wotten, Snell, & Glassgold 1979; Caselli et al. 1998). Balancing the CR-induced H_3^+ creation and destruction (via recombination with electrons and HCO^+ formation) rates, and those for HCO^+, created by $H_3^+ + CO \rightarrow HCO^+ + H_2$, and removed via e^- recombination and charge transfer reactions with metals (here assumed negligible), yields

$$\left[\frac{\mathrm{HCO^+}}{\mathrm{CO}}\right] = \frac{\mathrm{k(H_3^+, CO)}\,\zeta_{\mathrm{CR}}}{\mathrm{k_{HCO^+}\,k_e\,x(e)^2\,n(H_2)}}, \tag{4}$$

(e.g. Rohlfs & Wilson 1996) where $\zeta_{\mathrm{CR}}\,(\mathrm{s^{-1}})$ is the CR flux, and $\mathrm{x(e) = n_e/n(H_2)}$ is the free electron abundance. For $\mathrm{k(H_3^+, CO)} = 1.7 \times 10^{-9}\,\mathrm{cm^3\,s^{-1}}$ (the $H_3^+ - CO$ reaction rate; Kim et al. 1975), and $\mathrm{k_e} = 1.26 \times 10^{-6}\mathrm{T_k^{-1/2}\,cm^3\,s^{-1}}$ (McCall et al. 2003), $\mathrm{k_{HCO^+}} = 6 \times 10^{-6}\mathrm{T_k^{-1/2}\,cm^3\,s^{-1}}$ (the H_3^+ and HCO^+ dissociative recombination rates with e^-),

$$\left[\frac{\mathrm{HCO^+}}{\mathrm{CO}}\right] \sim 2.25 \times 10^{-5}\,\mathrm{T_k} \left(\frac{\zeta_{\mathrm{CR}}}{10^{-17}\,\mathrm{s^{-1}}}\right) \left[\frac{\mathrm{x(e)}}{10^{-7}}\right]^{-2} \left[\frac{\mathrm{n(H_2)}}{10^4\,\mathrm{cm^{-3}}}\right]^{-1}. \tag{5}$$

In dense cores in Galactic GMCs $\mathrm{x(e)} \sim 5 \times 10^{-9} - 1.5 \times 10^{-7}$ (Langer et al. 1985; Li et al. 2002) which, for $\mathrm{n(H_2)} \sim 5 \times 10^4\,\mathrm{cm^{-3}}$, $\mathrm{T_k} \sim 15\,\mathrm{K}$, and $\zeta_{\mathrm{CR}} \sim 3 \times 10^{-17}\,\mathrm{s^{-1}}$ yields $[HCO^+/CO] \sim 0.9 \times 10^{-4} - 0.08$, reflecting its sensitivity on the recombination with electrons even in the rather uniform environment of dense cores inside Galactic GMCs (the omitted charge transfer reactions of HCO^+ with metals make these estimates strict upper limits).

However, the dark, CR-dominated, dense regions in GMCs (where the bulk of the stars corresponding to a normal IMF forms) may not be representative of the typical ISM environments in LIRGs. There intense FUV and even X-ray (when AGNs are present) radiation fields may dominate and shift the dense gas chemistry towards photon-dominated rather than

CR-dominated processes. Nevertheless models of such photon-dominated regions (PDRs) yield mostly $[\mathrm{HCN/HCO^+}] > 1$, and observations of PDRs such as IC 63, NGC 2023, and the Orion Bar seem to confirm this by finding $\mathrm{N(HCN)/N(HCO^+)} \sim 1-5$ (Jansen 1995). Here must be noted that unexpectedly weak CN line emission with small CN/HCN ratios that decrease with increasing IR luminosity in LIRGs, casts doubts on the prevelance of PDRs for the bulk of their molecular gas reservoirs (Aalto 2004). This is because PDR models invariably predict very large CN/HCN ratios on the surfaces of FUV-illuminated clouds (e.g. Boger & Sternberg 2005), making this ratio one of the most effective diagnostics of their presence. Given the large extinctions found in LIRGs ($\mathrm{A_v} \sim 50-1000$; Genzel et al. 1998) it is possible that the FUV radiation from the newly formed O, B star clusters is effectively absorbed almost in situ around ultra-compact HII regions, and thus a lower ambient radiation field irradiates the bulk of the molecular gas in these galaxies.

The mostly low CN/HCN line intensity ratios found in LIRGs, many of which also host AGNs, signifies also a negligible contribution of X-ray Dissociation Regions (XDRs) to the *bulk* of the large molecular gas reservoirs found in these galaxies, since in XDRs $[\mathrm{CN/HCN}] \sim 5-10$ (Lepp & Dalgarno 1996). The well-studied case of the molecular gas in the starburst/AGN Seyfert 2 galaxy NGC 1068 shows the influence of XDRs limited to the small fraction of the total molecular gas residing close to the AGN (Tacconi et al. 1994; Usero et al. 2004), and in those regions one actually finds enhanced HCN and diminished $\mathrm{HCO^+}$ J=1–0 line intensities (Kohno et al. 2001). For more powerful AGNs XDR chemistry could become relevant for large fractions of molecular gas mass in the galaxies hosting them, and detailed work studying its effects on molecular abundances can help identify observationally accessible signatures (e.g. Maloney et al. 1996; Meijerink & Spaans 2005).

4.1. Turbulence, dense and ion-rich ISM in LIRGs: surpressors of the $\mathrm{HCO^+}$ abundance

The presence of turbulence in molecular clouds is now well established (e.g. Falgarone 1997), and its strong effects to their chemistry via the turbulent diffusion of the ion-rich (mostly $\mathrm{C^+}$) and electron-rich outer layers inwards have been demonstrated (Xie, Allen, & Langer 1995). *For turbulence levels easily attained in GMCs in LIRGs* x(e) *rises by an order of magnitude,* and $\mathrm{HCO^+}$ in dense cloud interiors then becomes surpressed by almost two orders of magnitude (Figs 2, 3 in Xie et al.), in approximate agreement with Equation 5 (for a constant CO abundance). Thicker $(\mathrm{C^+,e^-})$/C-dominated zones on GMC surfaces in LIRGs (a result of potentially larger FUV radiation fields) from which turbulent diffusion can draw $\mathrm{e^-}$-rich molecular gas inwards will further surpress $\mathrm{HCO^+}$. On the other hand the HCN abundance will be enhanced by the now larger quantities of C^+ and C in cloud interiors since they facilitate efficient HCN production (Boger & Sternberg 2005). Finally the shocks that are expected to be frequent in the highly supersonic turbulent molecular gas found in LIRGs, can also significantly reduce the HCO^+ while leaving the HCN abundance unperturbed (Iglesias & Silk 1978; Elitzur 1983).

In all cases where a high [HCN/HCO^+] abundance ratio is expected, a potentially larger portion of the dense gas phase may become more luminous through the HCN rather than the HCO^+ J=1–0 line emission and, depending of the level of line excitation, yield larger values of $M_{dense}(H_2)$ via Equation 3.

4.2. Effects favoring HCO^+ as dense gas tracer

In completely FUV-shielded environments photoionization is negligible and cosmic rays will be the sole cause of ISM ionization, and thus x(e) and ζ_{CR} are not expected to be independent. Following a treatment by McKee (1989)

$$x(e) = 2\times10^{-7}\left(\frac{n_{ch}}{2n(H_2)}\right)^{1/2}\left[\left(1+\frac{n_{ch}}{8n(H_2)}\right)^{1/2}+\left(\frac{n_{ch}}{8n(H_2)}\right)^{1/2}\right], \tag{6}$$

where $n_{ch}\sim 500\,\left(r^2_{gd}\,\zeta_{-17}\right)\,cm^{-3}$ is a characteristic density encapsulating the effect of cosmic rays and ambient metallicity on the ionization balance (r_{gd}: the normalized gas/dust ratio, $r_{gd}=1$ for Solar metallicities). From Equations 5 and 6,

$$\left[\frac{HCO^+}{CO}\right]\sim 2.25\times10^{-4}\,T_k\,r^{-2}_{gd}\left[\left(1+\frac{n_{ch}}{8n(H_2)}\right)^{1/2}+\left(\frac{n_{ch}}{8n(H_2)}\right)^{1/2}\right]^{-2}. \tag{7}$$

In the last expression [HCO^+/CO] appears much more robust in changes of the ambient ISM properties than in Equation 5 where x(e) and ζ_{CR} were considered independent. For gas dense enough to excite the HCO^+ J=1–0 line ($n_{cr}\sim 3.4\times10^4\,cm^{-3}$), and quiescent conditions typical of the Galaxy ($\zeta_{-17}\sim 1-3$, $n_{ch}\sim(500-1500)\,cm^{-3}$), it is $n_{ch}/(8n(H_2))\ll 1$ and [HCO^+/CO] is independent of gas density and CR flux. Only in starburst environments where $\zeta_{-17}=100-500$ (and thus $n_{ch}\sim(0.5-2.5)\times10^5\,cm^{-3}$), serious surpression of [HCO^+/CO] can occur in gas dense enough to excite the HCO^+ J=1–0 transition (e.g. [HCO^+/CO] $\sim(2-8)\times10^{-4}$ for $n(H_2)=10^4\,cm^{-3}$ and $T_k=15\,K$). However extensive observations of dense cores in Galactic GMCs do not support Equation 6, finding x(e) in most such regions to be much higher (Caselli et al. 1998). Inward turbulent transport of the outer cloud layers where x(e) is much higher because of photoinization could

It must be mentioned that not all the effects of turbulence on the HCO^+ abundance are negative since its intermittent dissipation in diffuse ($n(H_2) \sim 10^2 - 10^3\,cm^{-3}$) and warm ($T_k \sim 100 - 200\,K$) molecular gas can cause significant HCO^+ abundance enhancements but this process involves only small amounts of gas (Falgarone 2006).

Abundance ratios of $[HCN/HCO^+] > 1$ do not necessarily translate to similar line intensity ratios for the corresponding (in J level) HCO^+ and HCN transitions since their excitation characteristics differ. Their E_u/k_B values are similar but their critical densities $n_{crit}(HCN)/n_{crit}(HCO^+) \sim 5 - 7$ (for J=1–0, 3–2 and 4–3) and this will modify and can even reverse any abundance advantage that HCN may have over HCO^+ and make the transitions of the latter brighter. Indeed, given the density gradients expected in GMCs, even small differences in n_{crit} can translate to large differences in the extent of the cloud rendered "visible" via a particular transition. For the density-size relation: $\langle n(R) \rangle \propto R^{-1}$, and assuming gas remains "visible" via a particular molecular line out to a radius R_{cr} where $\langle n(R_{crit}) \rangle \sim n_{crit}$, the cloud mass ratio probed by HCO^+ and HCN (assuming equal abundances) will be

$$\frac{M_{HCO^+}(H_2)}{M_{HCN}(H_2)} \sim \left[\frac{R_{crit}(HCO^+)}{R_{crit}(HCN)}\right]^2 \sim \left[\frac{n_{crit}(HCN)}{n_{crit}(HCO^+)}\right]^2 \sim 25 - 49. \tag{8}$$

These values are only indicative, since optical depth effects, temperature, and abundance gradients will modify the aforementioned simple picture. Only observations of high-J lines for both molecules can discern the most comprehensive tracer of dense gas by comparing their respective (4–3)/(1–0), (3–2)/(1–0) line ratios as recently done by Greve et al. 2006.

Finally irrespective of which of the two molecules turns out as the most encompassing tracer of molecular gas at $n \geq 10^4\,cm^{-3}$, it may still include large amounts of gas not intimately involved in the star formation process. Indeed if observational studies of high-mass star-forming cores (Shirley et al. 2003) and recent theoretical advances (Krumholz & McKee 2005) are any guide, molecular gas with $n \gtrsim 10^5\,cm^{-3}$ is expected to be the true star formation fuel in the turbulent GMCs. Thus observations of high-J transitions of large dipole moment molecules such as those presented here, aside from yielding constraints on the excitation conditions of the dense gas phase, are a step closer to the true fuel of star formation in LIRGs, and a steping stone for revealing any universal aspects of this process in galaxies.

5. Conclusions

In this work sensitive new HCN J=4–3 observations of four prototypical Luminous Infrared Galaxies (LIRGs) are presented and combined with existing HCN J=1–0 measurements to probe the excitation properties of the dense gas ($n \geq 10^4\,cm^{-3}$) in these remarkable objects. The results, along with well-known effects that can severely affect the HCO^+ abundance, are used to insert the following important points in the ongoing debate regarding the relative merits of HCN and HCO^+ lines as dense gas mass tracers in such galaxies,

1. The large range of excitation conditions revealed from a *global* HCN (4–3)/(1–0) ratio varying by almost an order of magnitude ($\sim 0.1 - 1$) among the LIRGs observed here can severely hamper the methods advocated recently for dense gas mass estimates in such systems, by rendering the HCN or HCO^+ J=1–0 line luminosity and a "standard" conversion factor a poor proxy for that mass.

2. HCO^+, unlike HCN, is a molecular ion and thus easily destroyed by recombination with free electrons. Under most conditions in the dense gas regions of molecular cloud interiors this yields $[HCO^+/HCN] < 1$, especially in environments with enhanced electron abundances. In the turbulent and FUV-irradiated molecular gas in LIRGs such environments are expected to be common, and this effect could cause the low HCO^+/HCN line intensity ratios observed recently in such galaxies, especially towards high IR luminosities.

3. The lower critical densities of the HCO^+ rotational transitions than the corresponding ones (in J-level) of HCN will moderate and could even reverse the abundance advantage of the latter when it comes to line brightness. Thus, aside from yielding valuable constraints on what may be a considerable range of dense gas excitation properties, J=4–3, 3–2 observations for both molecules will help decide on their relative merits as dense gas mass tracers. Finally such high-J transitions can potentially trace the much denser ($n \gtrsim 10^5 - 10^6\,cm^{-3}$) molecular gas, thought to be the immediate fuel of star formation in LIRGs.

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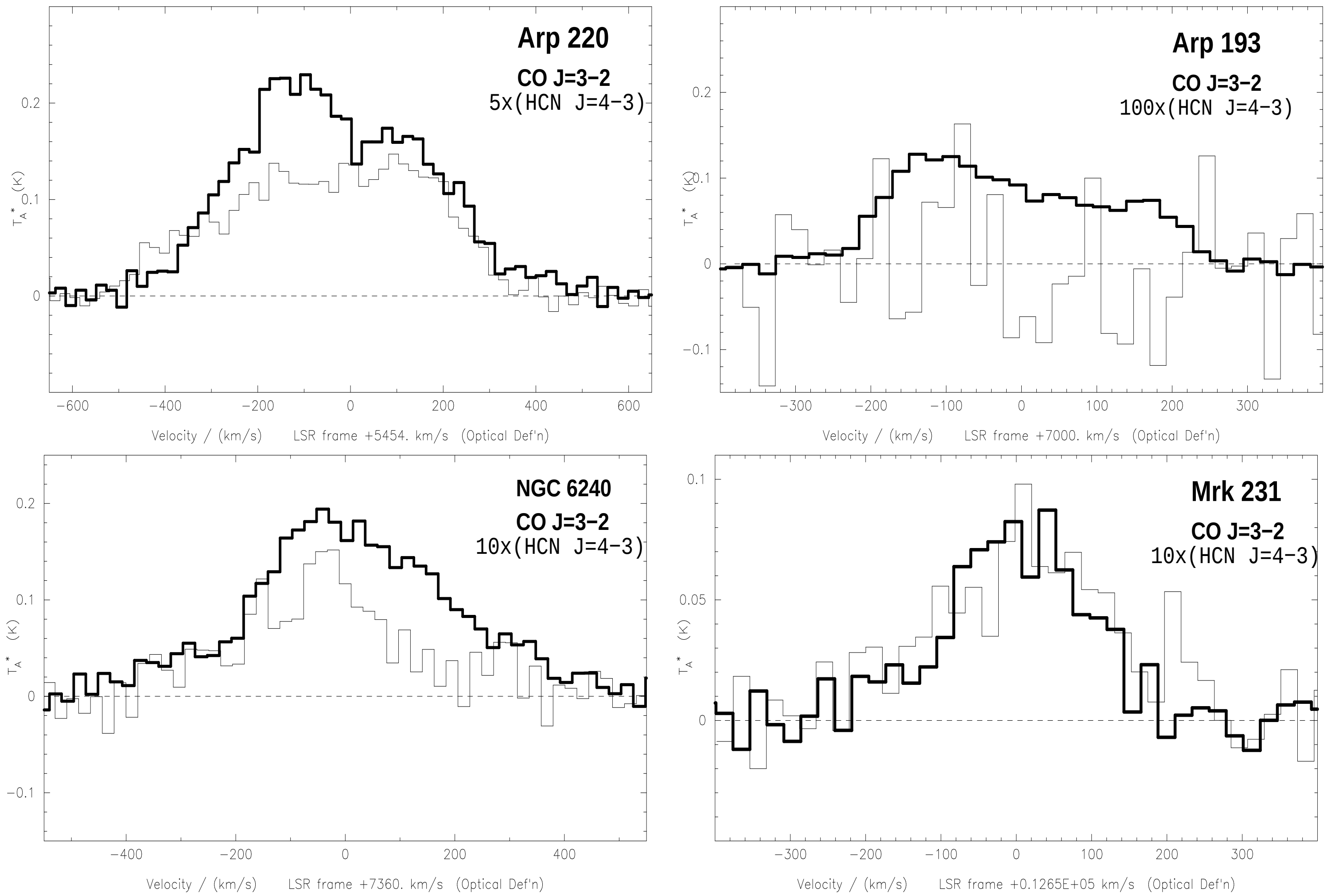

Fig. 1.— HCN J=4–3 (scaled by numbers given in the upper right), and CO J=3–2 spectra (bold line) of the four LIRGs at a common $\Delta\nu_{\rm ch} = 25\,{\rm MHz}\,(\sim 21\,{\rm km\,s^{-1}}$ at 350 GHz) resolution.

Table 1. HCN line intensities and ratios

Galaxy	L_{IR}[a] ($\times 10^{11}\,L_{\odot}$)	$\int S_{HCN(4-3)}dV$ Jy km s^{-1}	$\int S_{HCN(1-0)}dV$ Jy km s^{-1}	r_{43}(HCN)[b]
Arp 220	14	577 ± 105	36 ± 7[c]	1.00 ± 0.25
Arp 193	3.7	$\leq 10(3\sigma)$	5 ± 1[d]	≤ 0.12
Mrk 231	30.3	65 ± 13	15 ± 3[e]	0.27 ± 0.08
NGC 6240	6.1	130 ± 25	14 ± 2[f]	0.60 ± 0.15

[a]From Gao & Solomon 2004b.

[b]Brightness temperature ratios (T_b averaged over area/velocity).

[c]Average from Radford et al. 1991b, and Solomon et al. 1992.

[d]Garcia-Carpio private communication.

[e]From Solomon et al. 1992.

[f]From Greve et al. (2006)